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PROPOSAL FOR STUDY OF INTERACTION OF ELECTROMAGNETIC AND ACOUSTIC WAVES IN AN IONIZED MEDIUM

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ABSTRACT

"Radio-acoustic interaction" relates to the interaction that occurs between radio waves and acoustic waves in an ionized or partially ionized gas. Theory defines the general character of such interactions, with or without magnetic fields in the medium. A modulated radio wave can produce an acoustic disturbance which can react, in turn, either on the original wave or on another radio wave traversing the gas. An acoustic wave of any type whatever can modulate a radio wave in the medium. The proposed program involves two separate approaches, one mainly theoretical and the other experimental. The study is to include, in addition to basic research, a technical evaluation of the various types of radio-acoustic interaction as a practical means of reconnaissance, detection, or defense.

PROPOSAL FOR STUDY OF INTERACTION OF ELECTROMAGNETIC AND ACOUSTIC WAVES IN AN IONIZED MEDIUM

I. INTRODUCTION

It is well known that, in an ionized gas, a radio wave interacts with the electrons and ions, especially with the former since they are lighter and thus more subject to the accelerating effects of the electric field. In general, the index of refraction of the medium proves to be complex, so that radio waves traversing it are subject to absorption as well as to bending. The conventional theory of the propagation of a radio wave in the ionosphere depends upon certain implicit assumptions. The ionized medium is assumed to be quiet, undisturbed by acoustic waves or mechanical vibrations of any sort. The energy of the electromagnetic waves is assumed to be negligible, so that it does not appreciably change the temperature or mechanical state of the medium. The only effect treated consists of the instantaneous interaction between the electromagnetic wave and the electrons at any given position.

A preliminary analysis of a less restricted model, by Menzel and Layzer, has disclosed the existence of a number of hitherto unrecognized phenomena. In an ionized gas, a radio wave may interact with the electrons and ions and actually change the physical characteristics of the medium. The electron velocity during the interaction may no longer be Maxwellian, although in some instances it can be described as effectively Maxwellian at an electron temperature different from that of the ions or neutral atoms. The effect depends, of course, on the energy of the incident waves. And the phase of the disturbance relative to that of the incident wave depends on a number of factors, such as the modulation frequency and the collision frequency.

One may properly describe the phenomenon in terms of electromagnetic waves traversing the medium and setting up acoustic waves in the ionized gas. The acoustic waves, in turn, react on the electromagnetic waves, producing or altering their modulation. The presence of a permanent magnetic field in the medium also markedly affects the interaction.

The best known phenomenon that can be described in the above general terms is the so-called Luxembourg effect: the interaction of a modulated radio wave upon a second, unmodulated one via the acoustic field generated in the electron gas by the original modulated wave. But the basic analysis is far more general. It shows that a radio wave can interact with itself by means of the acoustic field. Or an acoustic field, however produced, may modulate any electromagnetic wave traversing the medium.

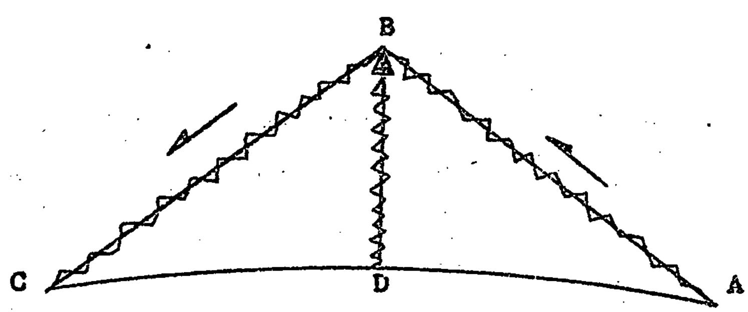

Figure 1

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Figure 1 illustrates, schematically, a well known phenomenon, the Luxembourgeffect. A radio station at A sends out an unmodulated signal, CW, on some frequency that is reflected from the ionosphere at B and finally received at C. This signal is sometimes termed the "wanted" wave. A transmitter at D, usually near the midpoint of the path, is radiating a modulated signal on a different frequency. Under certain conditions this signal, termed the "disturbing" or "unwanted" wave, modulates the wanted wave, so that the unwanted signal is received at C on the previously unmodulated wave.

The basic principles of the interaction are fairly well understood, because of fundamental work by Bailey and Martyn[1]. The wanted wave, during its passage through the ionosphere, suffers a certain amount of absorption whose magnitude depends on the electron collision frequency, ν, the gyro-frequency (determined by the general magnetic field), in addition to the radio frequency, ω. Bailey and Martyn showed that the disturbing signal could alter the physical state of the ionosphere: for example, the electron temperature and the frequency of electron collisions. This change would alter the absorption coefficient. Hence the wanted radio wave would be subject to absorption at the modulating frequency, μ.

Menzel and Layzer have shown that the main features of Bailey and Martyn's analysis follow directly from several simplifying assumptions and a linearization of the equations that gives an erroneous formula for the depth of the transferred modulation. It is proposed that these limitations be removed and that the whole problem of radio-wave interaction in an ionized medium be re-studied. Potential practical applications of the results and an experimental program should be suggested.

[1] V. A. Bailey and D. F. Martyn, Phil. Mag., 18, 369, 1934.

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An acoustic disturbance may arise from one of many sources: the explosion of a bomb or similar device in the medium, the shock and noise waves produced by a moving rocket or projectile, an audio disturbance from a sound transducer in the medium, convection or turbulence occurring naturally in the medium, irregular flow accompanying compression or dilatation of the medium by external forces such as an encounter of the ionosphere with solar ion clouds. The study suggests new ways of observing physical conditions in the ionized medium by virtue of induced modulation on radio waves.

This proposal includes suggestions for theoretical study of acoustic interaction. The first step represents completion of the elementary theory, to derive the actual velocity distribution of the electrons as a function of time, radio frequency, modulation frequency, collision frequency, and related physical parameters. The second step should extend the analysis to include the effects of gyro-frequency interaction resulting from the presence of a permanent magnetic field. Third, an experimental program should be initiated, to devise physical means of producing acoustic fields, together with various means of checking the theory and gathering information about the physical state of an ionized gas subjected to an acoustic disturbance.

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II. DISCUSSION

The conventional theory of radio propagation in an ionized medium implies the absence of acoustic disturbances. The medium is assumed to be static and unaffected by the waves traversing it, except for an instantaneous interaction between the electrons of the medium and the implied electric field of the radio waves. Most of the characteristics of radio wave propagation, such as critical frequency, maximum usable frequency, absorption coefficient, etc., can be predicted on the basis of this assumption.

However, if the radio wave is sufficiently powerful to produce mechanical oscillations in the ionosphere, the ordinary propagation equations do not apply. We have instead a modified form of the equations, which include terms that can be described as magnetohydrodynamic in character.

The equations describing oscillations in the medium do not separate into two distinct sets, one descriptive of electromagnetic and the other of acoustic phenomena, as they do when the medium is neutral. The presence of ions and associated electrons leads to coupling between the two varieties of disturbance. A magnetic field, if present, augments the coupling, which attains a maximum when the frequency of the radio wave equals the gyro-frequency of the magnetic field. As a result of the interaction, an acoustic disturbance may cross-modulate a radio wave traversing the medium.

The effect can be described as an interaction between an electromagnetic wave and acoustic waves in the medium or vice verse. A theoretical analysis of the phenomena involved has many useful and interesting applications.

Let the electric field of the incident wave be

$$E = E_0 \cos \omega t \cos \mu t,$$

where ω is the carrier frequency and μ the modulation frequency. The first stage of the analysis leads to results analogous to, but more general than, those derived by V. A. Bailey and D. F. Martyn[1] in a study of the Luxembourg effect. These conventional results are based on the implicit but nonetheless restrictive assumption that the interaction is independent of the modulation frequency, μ. This assumption holds strictly only for very low values of μ, for example when μ is less than 150 c/s. The second implicit assumption, that one can neglect changes in the physical state of the ion gas, appears to be justified.

why?

Let Q denote the mean thermal energy of an electron, w the mean rate of heating (per electron) by the radiation field, and R the mean rate of cooling (per electron) by collisions with the gas molecules. All of these quantities are functions of the time and describable by the differential equation representing the energy balance

$$dQ/dt = w - R .$$

For any given electric field, we know w. If we can find how R depends on Q, we can proceed to the solution. Linearization of the equations coupled with an assumed relation between Q and the collision frequency, ν, determines Q as a function of the magnitude of the impressed modulated field. This

[1] V. A. Bailey and D. F. Martyn, Phil. Mag., 18, 369, 1934.

leads, in turn, to an estimate of the depth of modulation of the electromagnetic wave.

The main restriction of the above conventional theory lies in the fact that Q, ν_0 and R are quantities averaged over a velocity distribution of the electron gas, f(q,t), where q is a velocity and t the time. If we can determine the velocity distribution as a function of the time, we can get a much clearer picture of the physical state of the medium. A detailed study proves that the depth of modulation as predicted by the simple theory proves to be incorrect.

One can make a start by using the Boltzmann transport equation, in connection with Maxwell's standard equations for the electromagnetic field. The transport equation leads to a non-linear differential equation of the second order, which can be reduced to the following comparatively simple form:

$$i \alpha y = x^r \left[(x-\tfrac{1}{2}) y' + xy'' - x^{3/2} e^{-x} \right]$$

where "dashes" indicate derivatives with respect to x. In the above equation, y represents the instantaneous net energy flux across a given surface by all electrons whose velocity is equal to or less than q. And x represents the energy of an electron moving with velocity q. Both y and x have been reduced to dimensionless form by division with values averaged with respect to time.

The parameter r is defined on the assumption that the collision frequency ν depends on the velocity q through a power law

$$\nu = \nu_0 x^r .$$

which defines both r and ν_o. Also,

$$\alpha = \frac{1}{2} \frac{\mu}{\nu_o} \frac{M}{m}$$

where μ is the modulation frequency. M and m are the masses of the neutral atoms and the free electrons, respectively. The quantity, i, has its usual significance, the square root of -1.

This equation has not been solved, except under some special, limiting conditions. The detailed solution, tabulated in terms of the two adjustable parameters, α and r, is the most urgent need. This will determine the distribution of electron velocities as a function of time and thus enable us to calculate directly the physical characteristics of the medium. This analysis will establish a firm basis for further study of the phenomenon of radio-acoustic interaction.

The second step, and one urgently needed, is the extension of the analysis to include the effects of a permanent magnetic field in the medium. At least four basic frequencies are involved: the radio or carrier frequency ω, the audio or modulated frequency μ, the gyro or Larmor frequency ξ, and the collision frequency ν.

The study should include, in addition to further improvement of the Luxembourg effect, an analysis of other allied phenomena of radio wave interaction. The "Inverse Luxembourg Effect", wherein the wanted and unwanted waves change places, is one example. The case of self-modulation or self-demodulation may also be relevant. The possible interaction of frequency modulated waves has also not been previously discussed.

For sake of completeness, the study should examine the feasibility of carrying out experiments to test the theory or to determine various physical characteristics of the ionized gas. A number of experiments are possible, of which the following is representative and perhaps the simplest. Suppose that the nose of a rocket contains a low-powered transmitter, operating on frequencies in the range from about 1.4 to 2.5 mc/sec. The gyro-frequency of the ionosphere, for intermediate latitudes, will tend toward the former value. However, in the presence of mechanical disturbances, possible compression of the medium or production of additional ionization may increase the gyro-frequency appreciably. Any rocket or missile traversing the ionosphere will set up acoustic vibrations which, by virtue of the expected non-linear interaction, can be expected to transfer acoustic modulation to the beam from the nose cone. One may encounter difficulties, however, in distinguishing between the expected low-frequency amplitude modulation and the variation of signal strength caused by changing aspect of the rocket.

Alternative varieties of ionospheric disturbances, including those produced by disruptions similar to that of an Argus effect, are relevant. The study may include the effect of normal acoustic noise existing in the ionosphere, such as that produced by convection or turbulence, as it may interact with electromagnetic waves traversing the medium.

The existence of radio-acoustic interaction has been demonstrated experimentally as well as theoretically. It is related to the well known Luxembourg effect, where the acoustic field induced by a powerful modulated radio wave serves to modulate another radio wave. The cross-modulation, which results from fluctuations in the absorption coefficient of the ionized layer, depends on the audio frequency. A second and closely related phenomenon is self-modulation, the interaction of a modulated radio wave with its own acoustic disturbance. This interaction may increase or decrease the

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original modulation, by an amount dependent on the audio frequency.

The Luxembourg effect definitely needs a thorough quantitative study to determine the basic facts of audio-radio wave interaction. This study requires the construction and operation of equipment to measure the percentage modulation at different audio and radio frequencies.

The power dependence of the interaction is as yet completely undetermined, in view of the fact that the "unwanted" wave has been taken from some existing station. Additional significant information will become available if the power of the "unwanted" beam can be varied as desired. The studies should include the effects of self-modulation as well as ordinary wave interaction.

Unless special efforts are made, the energy imparted to the acoustic field by the electromagnetic wave is small. The interaction is appreciable because a large volume is affected. The passage of a rocket or missile through the ionized medium creates a shock wave or major disturbance, which can appreciably affect the physical state of the medium, changing the gyro-frequency as well as producing a strong acoustic pulse. Explosions, atomic or otherwise, can cause similar disturbances. The question to be investigated, by both experimental and theoretical means, is the detailed character of the possible interactions between the acoustic disturbance and an electromagnetic wave. Specifically, what information can one expect to obtain from the signal received from such a region? Can this phenomenon be used for intelligence, reconnaissance or for the detection of ionospheric disturbances of artificial origin?

Experiments with rockets or missiles can give valuable data concerning the interaction between a radio wave and an impulsive acoustic disturbance produced by the vehicle. One example of a variety of experiments that could be performed in this field is given below. This particular experiment was proposed by Menzel in 1949 and instrumented in an Air Force experiment carried out at White Sands Proving Ground. Unfortunately, the rocket, one of the last of the old V2's, aborted. The experiment was never repeated.

The procedure calls, first of all, for a transmitter operating in the nose of the rocket and radiating CW on or near the expected gyro-frequency of the ionosphere. It is expected that the audio impulse of the shock wave will modulate the rocket signal that has to pass through the wake of the missile. Varying the radio frequency will give important data concerning the nature of the wave interaction.

Experiments have shown that radio waves, tuned to the gyro-frequency of a magnetic field, can produce luminosity in an evacuated bulb at considerable distance (half a kilometer or more) from a transmitter. The voltage is fed from an antenna to condenser plates so set that the electric field is perpendicular to the internal magnetic field. Tests have shown that even very low powers can yield appreciable luminosity.

In the primitive form, the luminous globes have potential practical application, such as providing illumination to an area not yet wired for electric current. But the principle, if intensified, has additional practical applications. Calculations indicate that semi-directed radio beams, operating at the terrestrial gyro-frequency, could appreciably enhance the electron density already present in the ionosphere. And there is also the possibility that, with sufficient energy, a glow discharge could be initiated, resulting in an artificial air glow or aurora. The enhanced ionization could be of great practical benefit, permitting communication on frequencies much higher than the ionosphere would normally sustain.

Finally, at the ultimate limit of high power, there is the definite question that still requires an answer. Could a focussed radio beam be used to destroy or render inoperative any metallic object it might encounter? Here the first study to be undertaken is largely theoretical. To answer such questions as the degree of heating, the effect of shock waves on gyro-frequency, and so on, such experiments might be done with the aid of the down-range facilities of Atlantic Missile Testing Range, Cape Canaveral, Florida, with observations on signals to and from missiles.

III. STATEMENT OF WORK

The contractor shall furnish the necessary personnel, services of others, facilities, and materials and shall use its best efforts to perform the following:

1. Extend the theory of radio-acoustic interaction to include the effects of such phenomena as:

(a) non-Maxwellian distribution of electron velocities;

(b) the heating of the medium by the presence of acoustic and electromagnetic waves;

(c) the interaction between electromagnetic and acoustic disturbances;

(d) the interaction between electromagnetic waves and shock waves;

(e) extension of the analyses to include the effects of magnetic fields in the medium;

(f) the effect of electromagnetic waves already present in the medium on the nature of the interaction, particularly through the medium of the gyro-frequency; and

(g) the frequency distribution of electromagnetic radiation induced by acoustic disturbances.

2. Carry out systematic experiments to investigate the specific phenomena of radio-audio interaction, with specific relation to the theory detailed above;

(a) determine the frequency and power dependence of cross-modulation in the Luxembourg effect;

(b) determine the nature of self-interaction in a modulated radio wave;

(c) investigate the nature of the interaction of radio waves with acoustic disturbances of various origins;

(d) determine the relationship between this interaction in the presence of magnetic fields;

(e) study the luminosity induced in evacuated globes with the aid of electromagnetic radiation fed to crossed electric and magnetic fields at the gyro-frequency;

(f) study the effect of gyro-interaction on radio waves emitted by missiles penetrating the ionosphere, as perturbed by the shock wave produced by the missile; and

(g) from the foregoing experiments and theory, determine the feasibility of causing excess ionization in the ionosphere, as the result of radio waves incident on the medium.

APPENDIX "A"

TYPICAL SENIOR PERSONNEL

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6 April 1960

MEMORANDUM FOR: [redacted]

SUBJECT : Use of the "Luxembourg Effect" as a Missile Launch Detection Technique

1. This memorandum presents a recommendation for action by the on the initiation of a technical surveillance project. This recommendation is presented in paragraph 5.

2. Background: The "Luxembourg Effect", more precisely termed "ionospheric cross modulation", was first observed in 1933 when reception at Eidenhoven, Netherlands, of a broadcast from Beromunster, Switzerland, was frequently disturbed by a weak background of a program from a radio station in Luxembourg. This interference was not due to defects in the receivers, or to local disturbances. The suggestion was made that it was due to interaction between the two radio waves as they passed through the ionosphere. Evidence accumulated rapidly to show that the phenomena did exist and was most marked when the desired broadcast signal was a medium wave received by ionospheric propagation and the disturbing signal was generated by a high powered long wave station located somewhere near the midpoint of the transmission path of the medium wave signal. Limited investigations of the effect continued through World War II when the cross modulation technique was used as a tool for ionospheric research. Not much direct application of the principle has been made since those experiments.

3. Problem: The need for more information regarding the Soviet missile test program has prompted the suggestion that the above mentioned "Luxembourg Effect" be utilized as a missile launch detection technique. With a suitable (50 KW) medium wave transmitter located in [redacted] STAT

The Soviet missile test launch area at Tyura Tam would be located at the mid-point of the transmission path and therefore provide a maximum intermodulation disturbance. (Evidence indicated that moving the disturbing signal source as little as 300 miles either way from the transmission mid-point will result in a decrease in cross modulation as great as 90 per cent. The reception of 50 KW medium frequency signals over ranges of 4,000 miles requires no special techniques and is fairly common place during winter nights. Atmospherics will probably limit the system's usefulness during the summer months.) The missile itself will provide the modulating signal. There is strong evidence that a missile penetrating the ionosphere sets up low frequency disturbances in it which should result in modulation of a medium frequency wave incident upon the ionosphere at the point of penetration. Detection of this medium frequency broadcast signal and its modulation would be enhanced with regard to other interfering signals if a directional Adcock antenna were used at the receiving site.

Memorandum for [redacted] dated 6 April 1960
Subj: Use of the "Luxembourg Effect" as a Missile Launch Detection Technique

4. Proposal: It is therefore proposed that a series of feasibility experiments be conducted under relatively controlled conditions against known missile launches. A near ideal geographic set-up is provided by locating a transmitting and receiving facility on a line running through the point of ionospheric penetration of missiles launched at Cape Canaveral. The receiving site, at which most of the work is to be done (signal analysis, etc.), should be located ideally in [redacted] STAT The transmitter site must necessarily be as far southwest of the penetration point as [redacted] is to the northeast. [redacted] offers such a location. STAT The remoteness of the transmitter site also has the advantages of minimizing the effects of a high powered broadcast transmitter on local broadcast reception. Some degree of freedom will be necessary in choosing the experimental test frequencies and the propagation modes.

It is further proposed that the system be instrumented to provide measurements of at least two particular phenomena. The first of these is the variation of the amplitude of the received signal strength with time. This effect might be determined by recording the AGC voltage of the receiver with sufficient time resolution and dynamic range to allow discrimination between normal fading amplitudes and fading rates and those that can be correlated with missile firings.

The second effect to be measured is that of phase changes in the received signal. Such phase changes (and associated Doppler frequencies) may be the result of the disturbance of the normal propagation path or an effect created by multi-path propagation. Whatever the mode of disturbance generation might be, instrumentation will require highly stabilized frequency sources for both the transmitter and the receiver.

In the system, the greater burden is on the receiving terminal. Although gross effects of signal disturbance might be observed, there is a much greater probability that the effects will be small. Consequently, the recording and data processing equipments must be capable of handling fine-structure signals for various correlation and analysis techniques. Fortunately, there is no requirement for real-time processing so that appropriate programing could make use of facilities such as [redacted] STAT

The reduced data from the proposed system should prove feasibility and may provide criteria for optimizing the future system design.

Memorandum for dated 6 April 1960
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5. __Recommendations__: It is recommended that the foregoing proposed feasibility study and experiment be implemented in the following manner:

a. should transfer funds to for running the project. ($150,000 estimated for operation for one year)

b. should let contracts through the various military agencies to do the following:

(1) Navy - Prepare the transmitter site, install power generation, transmitting, communications, and personnel facilities.

(2) Air Force/ARDC/CRC - Technical monitoring of the project, establishment of a receiving facility at [redacted] manning of both the transmitting and receiving facilities (by contractors, if necessary), supervising the data analysis and feasibility report preparation. STAT

(3) Navy - Provide the necessary logistic support for the transmitter facility.

c. should make proper arrangements with to keep up-to-date on the technical progress of the project.

CONCUR: